# An Inter-Comparison of Surface Energy Flux Measurement Systems Used During FIFE-1987

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## Abstract

During FIFE-87, surface energy fluxes were measured at 22 flux sites by nine groups of scientists using different measuring systems. A rover Bowen ratio station was taken to nearly all the flux stations to serve as a reference for estimating the instrument related differences. The rover system was installed within a few meters from the host instrument of a site. Net radiation, Bowen ratio and latent heat fluxes were compared between the rover and the host for the stations visited. Linear regression analysis was used to examine the relationship between rover measurements and host measurements. These inter-comparisons are needed to examine the influence of instrumentation on measurement uncertainty. Highly significant effects of instrument type were detected from these comparisons. Instruments of the same type showed average differences of less than 5% for net radiation, 10% for Bowen ratio and 6% for latent heat flux. The corresponding average differences for different types of instruments can be up to 10%, 30% and 20%, respectively. The Didcot net radiometer gave higher net radiation while the Swissteco type showed lower values, as compared to the corrected REBS model. The 4-way components mothed and the Thornswaite type give similar values to the REBS. The SERBS type Bowen ratio systems exhibit slightly lower Bowen ratios and thus higher latent heat fluxes, compared to the AZET systems. Eddy correlation systems showed slightly lower latent heat flux in comparison to the Bowen ratio systems.

## Introduction

One of the major goals of the First ISLSCP Field Experiment (FIFE) was to monitor the spatial variability of surface energy fluxes. During FIFE-1987, surface energy fluxes were measured at 22 sites over a 15 by 15 km natural grassland experiment area. This was accomplished by nine principal investigators (PI) who managed from 1 to 6 sites using his instruments of either Bowen ratio (BR) or eddy correlation (EC) technique at a site. A variety of instruments were used to estimate fluxes based on these two techniques with nine distinct sensor configurations and data reduction procedures distributed among the 22 stations.

A previous study had been conducted in 1986 to compare the two techniques and different types of instruments (Kanemasu et al., 1987). The preliminary results indicated large differences between the two techniques as well as among instruments. Similar differences had been reported in earlier technique and instrument comparisons ( Shuttleworth et al., 1988, Spittlehouse and Black, 1979, 1980). Since the flux measurements taken at multiple locations include differences due to different techniques and/or instruments in addition to the true site induced difference, it is important to identify the instrument related variability in the data pool.

One approach to identify the relative instrument error is to bring all the instrument configurations together for an inter-comparison at a single site. However, logistic considerations during FIFE-87 did not allow for this possibility. Therefore, it was decided to operate a single roving energy balance system (net radiation and Bowen ratio ) to all the other sites for the purpose of inter-comparison (Sellers and Hall, 1987). The roving instrument system (rover) was scheduled to visit each site and set up side by side with the instruments operating at the site (host) during the experimental period. The measurements by the rover would be compared to those by the host. Instrumental difference between two hosts can then be estimated based on their respective comparison with the rover.

The purpose of the rover was to provide a common reference for comparison among sites, not to assess the absolute accuracy of each set of instruments. A difference in the comparison between the rover and host does not imply inaccurate measurements of the host. It has been assumed that this basis for comparison remains independent of the time of year, hence one can compare flux measurements from different instruments at different sites and estimate probable site differences by reference to the rover.

## Materials and Methods

All the surface flux stations were operated during the four intensive field campaigns (IFC) of FIFE-1987. Sites 06(2132-BRK), 08(3129-BRK), 10(3414-BRK),

12(2915-BRK), 14(2516-BRK), 20(6340-BRL), 34(3479-BRL), 36(2655-BRL), 40(1246-BRL), 42(1445-BRL), and 44(2043-BRL) were also operated between IFCs. Table 1 gives the type of instruments (radiation and latent heat flux) used by all host stations. The rover system, operated by Kansas State University, was moved to most of these sites with one at a time when the host system was in operation. The days when the rover visited each site and the days selected for the comparison are also shown in Table 1.

The rover system used the Bowen ratio (BR) technique. A Radiation Energy Balance Systems (REBS)* double-dome net radiometer (model Q*4) was used to measure net radiation ( $Rn_{rover}$ ). It was calibrated against a transfer standard using the shading technique during the season, along with several other radiometers used in FIFE as listed in Table 2 (Kanemasu, 1988). Bowen ratio ($\beta_{rover}$ ) was determined by an AZET portable system (Gay and Greenberg, 1985). Because of the short time period for which the rover visited a site prevented obtaining representative measurements of soil heat flux by the rover, it was agreed that the rover would use the soil heat flux data measured by the host ( $G_{host}$ ).

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Therefore, the rover system obtained latent heat flux ($\lambda E_{rover}$) by:

$$\lambda E_{rover} = - ( Rn_{rover} + G_{host} ) / ( 1 + \beta_{rover} ) \qquad (1)$$

The rover system was always positioned within a few meters of distance from the host equipment at each site. It was run continuously to get at least 24 hours of good data when both the host and the rover equipment were functioning properly and the sky was reasonably clear. The rover did not visit site 10(3414-BRK) and 12(2915-BRK) as the weather did not cooperate with the schedule. Since these two sites (10(3414-BRK) and 12(2915-BRK)) used identical instruments to the rover and all the instruments used by Kansas State University (sites 06(2132-BRK), 08(3129-BRK), 10(3414-BRK), 12(2915-BRK), 14(2516-BRK) and rover) were calibrated together before the beginning of the 1987 experimental period, the completeness of the inter-comparison was only minimally impacted.

As Table 1 shows, the host net radiation fluxes were determined with five different types of instruments; latent heat fluxes and Bowen ratios were determined by either the eddy correlation technique (EC, 6 sites) or the Bowen ratio technique (BR, 16 sites). Three types of sonic anemometers and two types of hygrometers were used at the EC sites while four types of psychrometers were used at the BR sites. Site 16(4439-ECV) (EC) and site 18(4439-BRV) (BR) were co-located as were site 30(4268-ECG) (EC) and Site 32(4268-BRK) (BR). Data from the hosts were obtained for all sites which the rover visited but sites 4 for the purpose of this study. No comparison was made on site 16(4439-ECV). At site 06(2132-BRK), only the Bowen ratio was measured by the rover for the comparison.

After the experiment, it was found that the REBS Q*4 radiometer had different sensitivities to the longwave and shortwave radiation, and therefore gave values that were too high during the day and too low at night. The manufacturer suggested that the data collected with the Q*4 radiometer be corrected by using the following adjustments (personal communication with REBS):

For positive radiation (daytime):

$$Rn\ (W\ m^{-2}) = 0.8971\ Rn_m\ (W\ m^{-2}) + 1.85\ (W\ m^{-2}) \qquad (2)$$

For negative radiation (night time):

$$Rn\ (W\ m^{-2}) = 1.4608\ Rn_m\ (W\ m^{-2}) - 0.58\ (W\ m^{-2}) \qquad (3)$$

Here, $Rn_m$ represents the uncorrected net radiation measurements, whereas Rn represents the corrected net radiation values which are used for the comparisons reported here. All radiation data collected with the REBS Q*4, both rover and host, have been adjusted according to equations (2) and (3).

## Results and Discussion

The length of time when the rover was located at the host varied from site to site depending on weather conditions (see Table 1). To be consistent, one day of data (24 hours) was selected for comparison at each site. Net radiation data were separated for daytime ( $Rn_{rover} > 0$ ) and nighttime ( $Rn_{rover} < 0$ ) to examine the sensitivity of different radiometers to longwave and shortwave radiation. Because unrealistic values for latent and sensible heat fluxes occur when the Bowen ratios approach -1 and for $\beta$ when vapor pressure gradients approach 0, only data when $Rn > 100$ W $m^{-2}$ were used in the analysis of latent heat flux and Bowen ratio. The following statistical analyses were applied to the data.

1. Linear regression analyses were applied to the data from each site with the host data assigned as the dependent variable. The slopes and intercepts served as statistical criteria as to how well the two sets of measurements compared. A slope of one and a intercept of zero mean a complete agreement between the rover and the host. Therefore, the null hypotheses of slope=1 and intercept=0 are simultaneously tested. The values of slopes, intercepts and R squares for net radiation ( $Rn>0$, $Rn<0$ ) are given in Table 3 and the results for Bowen ratio and latent heat flux are given in Table 4. The D-W statistics (Durbin and Watson, 1951) were calculated for each data set to examine the auto-correlation of errors; these results indicate that auto-correlation was significant in only a few cases. Therefore, the regression comparison results are valid. In addition, the average difference of the two systems and the percentage error with respect to integrated value were also listed in Tables 3 and 4.

2. Differences between rover and host of each parameter were calculated, i. e. $\Delta Rn$ ($Rn_{rover}$ - $Rn_{host}$), $\Delta\beta$ ($\beta_{rover}$ - $\beta_{host}$) and $\Delta\lambda E$ ($\lambda E_{rover}$ - $\lambda E_{host}$ ). Since these differences were assumed to be instrument related and independent of sites, analysis of variance (AOV) is used to examine if these differences varied with instrument type. Data were divided into groups according to the type of instrument used to collect the data (i. e., $\Delta Rn$ according to radiometers, $\Delta\beta$ to psychrometers, and $\Delta\lambda E$ to both radiometers, psychrometers and their combinations). All the eddy correlation stations are considered as one group since they all measure latent heat fluxes directly. Range, mean and standard error of the mean of each instrument group are given in Tables 5 to 8. A T-test was applied to test if the means of these differences (rover - host) were zero; and the values of the significance level for rejecting the hypothesis of mean=0 are given along with the auto-correlation coefficients in Tables 5 to 8. If this P value is smaller than a criteria value (say 0.01), then the hypothesis of mean being zero is rejected, which means the instrumental difference between the host and the rover is significant at that criteria lever (0.01). The D-W statistics was used to test the significance of the auto-correlations. In seven cases significant auto-correlations were detected (indicated by Y after the coefficient ); in thirteen cases auto-correlations were not significant ( noted by N ) and for the other thirteen, no decision could be made from the D-W test. A significant and high auto-correlation coefficient may suggest a invalid T-test for that particular case.

Net radiation

The instruments for obtaining net radiation can be grouped into five categories: 1) by using a REBS Q*4 double dome net radiometer (sites 06(2132-BRK), 08(3129-BRK), 10(3414-BRK), 12(2915-BRK), 14(2516-BRK), 18(4439-BRV), 20(6340-BRL), 32(4268-BRK), 34(3479-BRL), 36(2655-BRL), 40(1246-BRL), 42(1445-BRL), 44(2043-BRL)); 2) by using a Swissteco net radiometer (sites 22(4609-ECW), 24(6912-BRW), 28(6943-ECW)), 3) by using a Thornthwaite net radiometer (site 30(4268-ECG)), 4) by using a Didcot net radiometer (site 26(8739-ECB)); and 5) by combining the directional components of the radiation balance based on measurements from 2 Eppley pyrgeometers for longwave radiation and 2 Eppley PSP pyranometers PSP for short-wave radiation (sites 02(1916-BRS), 38(1478-BRS)).

Generally, the net radiation comparisons between the rover and host show basic agreement for all sites. This can be seen from Fig. 1 where the host is plotted against the rover. The mean difference ($Rn_{rover}$-$Rn_{host}$) for positive radiation ranged from -19.7 $Wm^{-2}$ (5.7%) at site 38(1478-BRS) to 25.3 $Wm^{-2}$ (10.3%) at site 28(6943-ECW) (Table 3). However, the analysis of variance indicates the effect of radiometer type on $\Delta Rn$ is highly significant.

Better agreement, for both day and night, between rover and host at sites with REBS Q*4 net radiometer was obtained because the rover and the host used the same type of net radiometer. The slope of the linear regression varies from 0.9839 (site 08(3129-BRK)) to 1.0461 (site 34(3479-BRL)) for positive radiation and from 0.9729 (site 40(1246-BRL)) to 1.2069 (site 08(3129-BRK)) for negative radiation. all the intercepts were less than 7 $Wm^{-2}$. From Tables 5 and 6 we can see that the mean difference between the rover and hosts of the 9 sites was only -4.6 $Wm^{-2}$ with a standard error of 2.03 for positive radiation, and less than 1 $Wm^{-2}$ for negative radiation.

Compared to the hosts using Swissteco net radiometer, the rover (REBS) gives higher Rn values during the day with negative intercepts significantly different from zero (except at site 24(6912-BRW)). The average difference ($Rn_{rover}$ - $Rn_{host}$) for this group was 10.2 $Wm^{-2}$ with a standard error of 2.49 (Table 5) for daytime (positive) radiation, and 13.6 $Wm^{-2}$ with a standard error of 0.88 (Table 6) for nighttime (negative) radiation. The hypothesis that mean difference is zero is rejected at 0.1% for both day and night periods from the T-test. The greater absolute difference at night may indicate differences in sensitivities to short and long wave radiation between the two types of radiometers.

The net radiation obtained by measuring the 4 components at site 02(1916-BRS) was very similar to that measured by the rover REBS Q*4. Although the intercept from the regression was -27.8 $Wm^{-2}$ for daytime and -14.9 $Wm^{-2}$ for night, the average $\Delta Rn$ was negligible for both cases (see Table 3). At site 38(1478-BRS), in which Rn was also determined from the 4 directional components, the host gave slightly higher net radiation during the day compared to the rover. The average difference was close to -20 $Wm^{-2}$ (-5.7%). For negative radiation, $\Delta Rn$ was only -3.3 $Wm^{-2}$. The mean of $Rn_{rover}$ - $Rn_{host}$ for both 4-component sites was -8.8 $Wm^{-2}$ (standard error=4.35) for positive radiation; this is significantly different from zero at the 5% level (Table 5). For negative radiation, the mean difference was -1.5 $Wm^{-2}$ (Table 6).

The Didcot radiometer exhibits higher net radiation values than the REBS at site 26(8739-ECB) with an average $\Delta Rn$ of -18.1 $Wm^{-2}$ (-4.8%) during the positive radiation period. For the negative radiation period, the Didcot measured less negative radiation than the REBS with average $\Delta Rn$ being -27.4 $Wm^{-2}$ (48.8%). Again, the greater nighttime $\Delta Rn$ may suggest differences in sensitivities to longwave and shortwave between the two radiometers.

The Thornthwaite at site 30(4268-ECG) gives almost the same average radiation as the REBS rover for both positive and negative radiation (see Tables 3, 5, 6). However, the linear regression analysis shows a very significant intercept of -27.6 $Wm^{-2}$ for positive radiation and -16.6 $Wm^{-2}$ for negative radiation. The host radiation values are slightly higher when Rn is greater than 400 $Wm^{-2}$ but a little lower when $Rn<300$ $Wm^{-2}$, in conjunction with the rover measurements (Fig. 1d).

Bowen ratio

Several types of Bowen ratio systems were used (see Table 1): 1) the AZET system (Gay and Greenberg, 1985) used at sites 06(2132-BRK), 08(3129-BRK), 10(3414-BRK), 12(2915-BRK), 14(2516-BRK), 18(4439-BRV) and the rover; 2) the SERBS (Fritschen and Simpson, 1989) used at sites 20(6340-BRL), 34(3479-BRL), 36(2655-BRL), 40(1246-BRL), 42(1445-BRL) and 44(2043-BRL); 3) the CSI, cooled mirror Dew-10 system (Smith et al, 1991) used at sites 02(1916-BRS), 32(4268-BRK) and 38(1478-BRS); and 4) the USGS system at site 24(6912-BRW). There were six eddy correlation systems at sites 4, 16(4439-ECV), 22(4609-ECW), 26(8739-ECB), 28(6943-ECW) and 30(4268-ECG) with 3 types of sonic anemometers and 2 types of hygrometers. These sites are classified as one group in the analysis of variance.

The rover and the host generally detect the same diurnal behavior of the Bowen ratio regardless of sites. However, the $\beta$ differences between rover host show considerable variations. The slopes of the linear regressions change from 0.543 at site 30(4268-ECG) to 1.534 at site 26(8739-ECB). In 11 out of 18 cases the intercepts are significantly different from zero (Table 4). Fig. 2 shows some scatter when the host $\beta$ is compared to the rover $\beta$. Significant instrument effects on $\beta_{rover} - \beta_{host}$ was detected from analysis of variance (Table 7).

Again, there is better agreement between the rover and the host when the same types of instruments are used. The AZET psychrometers' used at sites 06(2132-BRK), 08(3129-BRK), 14(2516-BRK), and 18(4439-BRV) are equivalent to those used by the rover. These sites show closer comparison in Bowen ratio than other sites (Table 3 and Fig. 2a). The slopes of the linear regressions vary from 0.817 to 1.105. The mean of $\beta_{rover}$ -$\beta_{host}$ for all four sites is 0.0010 with a standard error of 0.0140 and a P value for the T-test of 0.9404. For sites 06(2132-BRK), 14(2516-BRK) and 18(4439-BRV), the difference in $\beta$ between the rover and the host is less than 0.1 or 5%, whichever was greater, with very few exceptions. The variance at site 08(3129-BRK) is larger, probably due to more complexity of topographical characteristics.

At sites 20(6340-BRL), 34(3479-BRL), 36(2655-BRL), 40(1246-BRL), 42(1445-BRL) and 44(2043-BRL), which used SERBS psychrometers, both rover and host agree well in terms of the diurnal variation. In addition, the difference in $\beta$ between the two systems remain stable over time. The slopes of the linear regressions vary from 0.854 to 1.093. This range is nearly identical to the range of slopes in the AEZT group. The intercepts are negative for all 6 sites and 5 out of 6 are statistically significant at 5% level (Table 4). The mean of $\Delta\beta$ is 0.0861 with a standard error of 0.0086. The hypothesis that mean $\Delta\beta$ is zero can be rejected at the 0.01% level. The host system gave a consistently lower Bowen ratios at these sites compared to the rover, with the exception of site 44(2043-BRL), at which the rover and the host agreed very well. This suggests a constant difference between the

AZET and SERBS systems during FIFE-1987.

The comparison between the AZET rover and the Dew-10 systems was more complicated, as shown by the scatter in Fig. 2c. Relative to the rover, the Bowen ratios was systematically lower at site 2, shifting between high and low at site 32(4268-BRK) and a little higher at site 38(1478-BRS). The mean of $\Delta\beta$ is 0.0133 with standard error of 0.0155. The USGS model at site 24(6912-BRW) is less responsive than the rover over the range of 0.05 to 0.25. But overall, both types of Bowen ratio system gave very similar measurements, with a average difference ($\beta_{rover}$ -$\beta_{host}$) of 0.0181 and a standard error of 0.0688.

Four eddy correlation systems were compared with the rover Bowen ratio system at sites 22(4609-ECW), 26(8739-ECB), 28(6943-ECW), and 30(4268-ECG). The eddy correlation systems provide independent estimates of sensible (H) and latent ($\lambda$E) heat fluxes. The Bowen ratios are calculated as the ratio of H/$\lambda$E. The average difference ($\beta_{rover}$ -$\beta_{host}$) is -0.0201 with a standard error of 0.0305. The host systems gave slightly higher $\beta$'s at sites 28(6943-ECW) and 30(4268-ECG), but lower $\beta$'s at sites 22(4609-ECW) and 26(8739-ECB), compared with the rover system. Site 28(6943-ECW) is not shown in Fig. 2d because at this site the Bowen ratio went off the high end of the scale.

Differences in individual half hour retrievals of $\beta$ of more than 15% are common. Even for sites with identical instruments (e.g. sites 06(2132-BRK), 08(3129-BRK), 14(2516-BRK) and 18(4439-BRV) ), the differences in $\beta$ could still reach 10%. This may be due to some extra sources for difference, such as the value of the psychrometric constant each individual PI used, how each PI calculated the half hour average, etc. These factors makes up to 3-5% difference in Bowen ratio even if the temperature and vapor pressure gradients are the same. When the gradients are small, a slight difference in gradients could cause large difference in $\beta$. The comparisons show that when the measured $\beta$ was low (less than 0.4), the percentage difference are larger, and the slopes of the regressions are further from 1, compared to cases when $\beta$ was close to or exceed 1. The sites (sites 22(4609-ECW), 24(6912-BRW), 26(8739-ECB), 30(4268-ECG) and 32(4268-BRK)) which had a slope value either less than 0.8 or greater than 1.2 (see Table 4) in the linear regression, had an average Bowen ratio of less than 0.35.

Latent heat flux

For the Bowen ratio sites, the comparison results for latent heat flux are affected by the differences in both net radiation and Bowen ratios because it is based on partitioning the available energy. For eddy correlation sites, latent heat fluxes are measured directly. Therefore, in the analysis of variance, data are classified into groups according to the combinations of the radiometers and psychrometers for the BR sites, where as all the eddy correlation sites are in one group. Linear regression analysis has been applied to each site. The rover was unable to calculate latent heat flux at site 26(8739-ECB) because the host soil heat flux data was not available.

The overall comparisons between the rover $\lambda E$ and host $\lambda E$ are in good agreement considering the varieties of instruments involved. The slopes in the linear regression varied from 0.8838 to 1.3344, except for site 28(6943-ECW), at which comparisons were made during a period of low $\lambda E$ (IFC4). The mean $\Delta\lambda E$ ($\lambda E_{rover}$ - $\lambda E_{host}$) varied from -23.5 $Wm^{-2}$ (9.7%) to 65.9 $Wm^{-2}$ (-18.7%), for most sites it was less than 30 $Wm^{-2}$ or 10% of full scale (see Table 4). A significant instrument effect on $\Delta\lambda E$ is found in the analysis of variance.

Sites 06(2132-BRK), 08(3129-BRK), 14(2516-BRK) and 18(4439-BRV) used identical instruments to the rover (REBS Q*4 net radiometers and AZET psychrometers) and thus show the best agreement. The slopes of the regression are 1.0038, 0.9804 1.1063 and 1.0275, respectively. The grand mean of $\Delta\lambda E$ of all 4 sites was 9.5 $Wm^{-2}$ with a standard error of 5.32. The mean is not statistically significantly different from zero. Fig. 3a shows the comparison between the host $\lambda E$ (vertical axis) and rover $\lambda E$ (horizontal axis). Except for site 08(3129-BRK), as explained earlier, data from these sites closely followed the 1:1 line.

For sites using a REBS Q*4 radiometers and SERBS psychrometers (sites 20(6340-BRL), 34(3479-BRL), 36(2655-BRL), 40(1246-BRL), 42(1445-BRL), and

44(2043-BRL)), the host shows consistently higher (more negative) latent heat fluxes except for site 44(2043-BRL). The average $\Delta\lambda E$ vary from 4.1 $Wm^{-2}$ (-1.3%) at site 44(2043-BRL) to 65.9 $Wm^{-2}$ (-18.7%) at site 20(6340-BRL). The grand mean $\Delta\lambda E$ of this group is 29.1 (standard error=2.63). The hypotheses that the mean is zero was rejected at the 0.01% level (Table 8). This is evident in Fig. 3b. For the most part, data from these sites are above the 1:1 line. The higher host latent heat fluxes arise from the lower host Bowen ratio as discussed earlier.

For sites using the component method for obtaining net radiation and the CSI Dew-10 apparatus for obtaining Bowen ratio (sites 02(1916-BRS) and 38(1478-BRS)), the host $\lambda E$'s are slightly higher at site 02(1916-BRS) (average $\lambda E_{rover}$ - $\lambda E_{host}$ being 10.3 $Wm^{-2}$ or -4.6%) but slightly lower at site 38(1478-BRS) (average $\Delta\lambda E$ being -6.5 $Wm^{-2}$ or 2.7%), compared to the rover $\lambda E$. The grand mean $\Delta\lambda E$ of the this group is -1.9 $Wm^{-2}$ (standard error 4.13) and is not statistically different from zero.

At site 32(4268-BRK) the radiometer used was the same as the rover whereas the Bowen ratios were based on the Dew-10. The rover $\lambda E$'s are slightly lower than the host $\lambda E$'s with a average difference of 8.5 $Wm^{-2}$ (standard error 3.52) or -3.7% because of the slightly lower host Bowen ratio (mean $\beta_{rover}$ is 0.33 and mean $\beta_{host}$ was 0.28). This is significant at the 5% level. At site 24(6912-BRW) which used a Swissteco net radiometer and the USGS psychrometers, $\Delta\lambda E$ ($\lambda E_{rover}$

- $\lambda E_{host}$) averaged 15.1 $Wm^{-2}$ or -6.0%.

For the eddy correlation sites, all the energy balance components are independent measurements and there are residuals in the energy balance (e.g. Rn+G+H+$\lambda$E). Frequently the residuals could be relatively large (for example, residuals as high as 160 $Wm^{-2}$ are found at site 22(4609-ECW) on day 228). In the energy balance-Bowen ratio approach, all the available energy (Rn+G) is partitioned into H and $\lambda$E. On occasion, this leads to discrepancies between the rover Bowen ratio measurements and the host eddy correlation measurements. The host $\lambda$E's are generally smaller (less negative) than the Rover $\lambda$E's in Fig. 3c. The average difference in $\lambda$E ($\lambda E_{rover}$ - $\lambda E_{host}$) was -6.8 $Wm^{-2}$ (2.7%), -15.2 (22.6%) and -23.5 (9.7%) for site 22(4609-ECW), 28(6943-ECW) and 30(4268-ECG), respectively. The mean of $\Delta\lambda E$ for this group was significant at 1% level.

The net radiation was extremely important for the latent heat flux in the Bowen ratio energy balance. The effect on $\lambda$E of radiometer type seemed to be more important than that by the Bowen ratio instrument although both effects were highly significant (Table 8, AOV).

## Summary and Conclusions

A Bowen ratio energy balance system operated as a mobile inter-calibration system visited 20 of the 22 surface flux sites during FIFE-1987. The rover system was installed close to the host system. The rover measured net radiation and Bowen ratio directly at each site. Based on these measurements and the soil heat flux measured by the hosts, the rover latent heat flux was calculated. The rover data are used to provide a reference for detecting instrument related measurement differences, although the rover cannot be considered as an absolute calibration standard. The following conclusions are drawn from the inter-comparison:

1. Significant differences in instantaneous measurements related to instrumentation are found in the variables compared (net radiation, Bowen ratio and latent heat flux). Instruments of the same type exhibited better comparison than instruments of different type. The same type of net radiometers exhibit an average differences not exceeding 10 $Wm^{-2}$ but for different type of model the differences can be up to 27 $Wm^{-2}$. With regards to latent heat flux, equivalent instrument models show average differences of less than 6%, however, different types of instruments exhibit difference up to 20%.

2. Differences caused by factors other than true site variation can not be neglected. The differences in net radiation due to different net radiometers can reach 100 $Wm^{-2}$ for a single half hour average, differences in $\beta$ for differing instruments can be more than 30% at given times during the day. These differences directly impact the sensible and latent heat fluxes differences when the fluxes are

determined by the Bowen ratio technique. In general, differences due 'to net radiometers have greater influence on comparisons of latent heat fluxes than difference arising from the psychrometer measurements.

3. Differences between the rover net radiation and host net radiation were relatively larger for negative net radiation (Rn<0) than for positive net radiation (Rn>0) for some hosts with different radiometers. This points to differences in sensitivity to longwave and shortwave radiations among the various radiometers.

4. Based on the inter-comparisons, it could be expected that site with the Didcot radiometer (site 26(8739-ECB)) exhibits higher net radiation value, and sites with the Swissteco radiometers showed a little lower value of Rn, compared to sites with the REBS Q*4 and sites with 4-way components method. Sites using the SERBS psychrometers might exhibit slightly lower Bowen ratio and thus higher latent heat flux than those using the AZET design. The eddy correlation sites would show slightly lower latent heat flux than the Bowen ratio sites.

The rover was only stational for a short period of time at each site. Therefore, the inter-comparisons do not involve statistical analysis at extended time series. Instead, they focus on relative differences that can arise between different instrument models for instantaneous measurements. Ideally, relative difference showed in the inter-comparison would not be influenced by the time of year. In some instances, however, the condition of instruments could change during the season. For example, contaminated wicks, poor ventilation, or dirty domes could cause error. These conditions could have been different between the host and the rover instruments at the time when the rover was visiting. In addition, the particular environmental and biophysical conditions at the sites and their changes in the course of the growing season could also affect the results of the comparison since different types of instruments could show different responses to different conditions. For example, emissivity and reflectivity variation of the surface could influence the radiation comparison if the radiometers differ in sensitivity to long and short wave radiation. However, these factors represent the actuality of conducting inter-comparison in the field and thus are intrinsically related to relative uncertainly between different instruments. In general, the rover inter-comparison provide a useful reference against which the spatial variabilities of the fluxes can be examined.

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## List of Figures

*Table 1. Days when the Rover Visited Each Site and Days Selected for Comparison Sky Conditions for the day Selected and Host Instrumentation*

| Sites | Days visited | Day(s) selected | Sky condition | Host instruments | |
|---|---|---|---|---|---|
| | | | | for radiation | for latent heat # |
| **02** | 220-224 | 221 | clear | components | BR(Campbell Sci.) |
| **04** | 190-192 | * | * | | EC |
| **06** | 240-242 | 241 | clear | REBS Q*4 | BR(AZET) |
| **08** | 208-214 | 210 | mostly sunny | REBS Q*4 | BR(AZET) |
| **10** | - | - | didn't visit | REBS Q*4 | BR(AZET) |
| **12** | - | - | didn't visit | REBS Q*4 | BR(AZET) |
| **14** | 215-219 | 218 | mostly sunny | REBS Q*4 | BR(AZET) |
| **16** | + | + | + | | EC |
| **18** | 231-233<br>171-178 | 232 | clear | REBS Q*4 | BR(AZET) |
| **20** | 158-170 | 167 | clear | REBS Q*4 | BR(SERBS) |
| **22** | 227-229 | 228 | clear | Swissteco | EC |
| **24** | 229-231 | 230 | partly cloudy | Swissteco | BR(USGS) |
| **26** | 193-197 | 195 | mostly sunny | Didcot | EC |
| **28** | 155-157<br>284-288 | 286 | mostly sunny | Swissteco | EC |
| **30** | 187-193 | 189-190 | mostly sunny | Thornthwaite | EC |
| **32** | 187-193 | 189-190 | mostly sunny | REBS Q*4 | BR(Campbell Sci.) |
| **34** | 182-187 | 185 | partly cloudy | REBS Q*4 | BR(SERBS) |
| **36** | 177-181 | 180 | partly cloudy | REBS Q*4 | BR(SERBS) |
| **38** | 224-227 | 226 | clear | components | BR(Campbell Sci.) |
| **40** | 197-200 | 199 | clear | REBS Q*4 | BR(SERBS) |
| **42** | 201-205 | 202 | clear | REBS Q*4 | BR(SERBS) |
| **44** | 152-155 | 154-155 | clear | REBS Q*4 | BR(SERBS) |

# BR: Bowen ratio
EC: Eddy correlation

* Data not available

\+ Did not compare

*Table 2. Radiometer Calibration Results (from Kanemasu, 1988)*

| from site | type | serial # | calibration (W $m^{-2}$ $mV^{-1}$) new | original |
|---|---|---|---|---|
| rover | REBS | 87033 | 11.59+0.15 | 11.5 |
| site 18 | REBS | 87050 | 11.33+0.14 | 11.5 |
| site 40 | REBS | 87060 | 12.43+0.14 | 12.5 |
| site 24 | Swissteco | 7377 | 20.50+0.25 | 20.0 |
| site 30 | Thornthwaite | 511 | 182.18+2.77 | 190.6 |

*Table 3. Statistical Comparison of Net Radiation between the Host System and the Rover at the FIFE Sites*

| Sites | Daytime radiation (Rn>0) | | | | | Nighttime radiation (Rn<0) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | slope | intercept | R-square | % error | ΔRn | slope | intercept | R-square | % error | ΔRn |
| 02 | 1.0769** | -27.8** | 0.992 | 0.4 | 1.4 | 0.2894*** | -14.9*** | 0.186 | -2.6 | 0.5 |
| 08 | 0.9839 | 6.8 | 0.990 | -0.6 | -1.8 | 1.2069*** | 10.9*** | 0.965 | 2.1 | -1.0 |
| 14 | 1.0084 | 2.4 | 0.996 | -1.7 | -4.9 | 0.9917 | 3.1*** | 0.999 | 6.6 | -3.5 |
| 18 | 1.0215 | -7.1 | 0.998 | -0.7 | -2.1 | 1.0631 | -1.6 | 0.996 | 6.1 | 2.9 |
| 20 | 1.0241 | 1.5 | 0.997 | -2.8 | -10.2 | 1.0248 | 0.4 | 0.987 | -1.6 | 0.8 |
| 22 | 1.0347 | -28.4*** | 0.997 | 4.4 | 15.8 | 0.9862 | -11.8*** | 0.939 | -26.7 | 11.2 |
| 24 | 1.0540* | -7.6 | 0.990 | -2.8 | -8.1 | 1.4715*** | 2.5 | 0.949 | -35.5 | 7.7 |
| 26 | 1.1451*** | -36.2*** | 0.999 | -4.8 | -18.1 | 0.5888*** | 4.3 | 0.949 | 48.8 | -27.4 |
| 28 | 1.0329 | -33.4*** | 0.997 | 10.3 | 25.3 | 1.2649** | -11.1** | 0.874 | -57.0 | 20.7 |
| 30 | 1.0900*** | -27.6*** | 0.996 | -0.7 | -2.2 | 0.5823*** | -16.6*** | 0.922 | 2.8 | -1.2 |
| 32 | 1.0022 | -0.2 | 0.988 | -0.2 | -0.6 | 0.9910 | -2.4* | 0.989 | -4.8 | 2.0 |
| 34 | 1.0461* | -0.4 | 0.993 | -4.4 | -7.3 | 1.1037** | 1.4 | 0.991 | -5.8 | 1.8 |
| 36 | 1.0132 | -0.7 | 0.994 | -0.8 | -1.3 | 1.0810* | 1.3 | 0.981 | -1.6 | 0.3 |
| 38 | 1.0832** | -9.0 | 0.985 | -5.7 | -19.7 | 1.1334* | 6.7*** | 0.955 | 13.3 | -3.3 |
| 40 | 1.0108 | -2.3 | 0.996 | -0.5 | -1.8 | 0.9729 | -1.8** | 0.993 | -3.0 | 0.9 |
| 42 | 1.0125 | 4.1 | 0.998 | -2.4 | -8.5 | 1.1888** | 4.2 | 0.964 | -9.7 | 4.5 |
| 44 | 1.0120 | 0.3 | 0.986 | -1.3 | -4.8 | 1.0274 | 0.3 | 0.935 | -2.3 | 1.4 |

host($Wm^{-2}$) = slope * rover($Wm^{-2}$) + intercept($Wm^{-2}$)
% error = (integrated rover - integrated host)/integrated rover
ΔRn ($Wm^{-2}$) = average rover Rn - average host Rn
***, **, * significant at 0.1%, 1%, 5% level, respectively, for reject hypothesis slope=1 or intercept=0

*Table 4. Statistical Comparison of Bowen Ratio and Latent Heat Flux between the Host System and the Rover at the FIFE Sites for Time Period when $Rn > 100\ Wm^{-2}$*

| sites | Bowen ratio | | | | | latent heat flux | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | slope | intercept | R-square | mean-R | mean-H | slope | intercept | R-square | % error | $\Delta\lambda E$ |
| 02 | 0.9742 | -0.065* | 0.965 | 0.654 | 0.566 | 1.3344*** | 65.3*** | 0.954 | -4.6 | 10.3 |
| 06 | 1.1045* | -0.015 | 0.960 | 0.730 | 0.760 | 1.0038 | 3.8 | 0.986 | 1.4 | -3.0 |
| 08 | 0.8178 | 0.106 | 0.706 | 0.912 | 0.838 | 0.9804 | -14.4 | 0.893 | -5.8 | 10.8 |
| 14 | 0.9216 | 0.026 | 0.969 | 0.290 | 0.290 | 1.1063 | 26.7 | 0.906 | -1.7 | 5.1 |
| 18 | 0.9238 | 0.038** | 0.945 | 0.255 | 0.285 | 1.0275 | 21.2 | 0.956 | 4.6 | -14.3 |
| 20 | 0.8545* | -0.129*** | 0.904 | 0.067 | -0.072 | 1.1757*** | -3.9 | 0.988 | -18.7 | 65.9 |
| 22 | 0.5901*** | 0.056** | 0.902 | 0.352 | 0.263 | 1.1069 | -34.2 | 0.907 | 2.7 | -6.8 |
| 24 | 0.5674*** | 0.061** | 0.865 | 0.177 | 0.159 | 1.1864** | 31.6* | 0.963 | -6.0 | 15.1 |
| 26 | 1.5308* | -0.243** | 0.818 | 0.340 | 0.280 | | | | | |
| 28 | 1.0327 | 0.151 | 0.798 | 2.789 | 3.036 | 0.6474** | -9.1 | 0.578 | 22.6 | -15.2 |
| 30 | 0.5435*** | 0.149*** | 0.867 | 0.327 | 0.335 | 1.1734 | 65.2** | 0.852 | 9.7 | -23.5 |
| 32 | 0.5826*** | 0.091 | 0.614 | 0.330 | 0.280 | 0.9398 | -22.3 | 0.903 | -3.7 | 8.5 |
| 34 | 1.0747 | -0.106** | 0.751 | 0.301 | 0.219 | 1.1457 | -3.4 | 0.832 | -16.3 | 31.8 |
| 36 | 1.0883 | -0.079*** | 0.653 | 0.080 | 0.009 | 1.0271 | -8.3 | 0.983 | -8.1 | 12.5 |
| 38 | 1.2035 | 0.049 | 0.834 | 0.354 | 0.475 | 0.8838 | -21.7 | 0.899 | 2.7 | -6.5 |
| 40 | 0.9460 | -0.126* | 0.758 | 0.482 | 0.331 | 0.9656 | -35.2*** | 0.981 | -10.6 | 26.6 |
| 42 | 0.9144 | -0.044* | 0.843 | 0.190 | 0.130 | 1.1144* | 9.0 | 0.982 | -8.7 | 29.2 |
| 44 | 1.0691 | -0.011 | 0.970 | 0.189 | 0.191 | 0.9747 | -11.9 | 0.938 | -1.3 | 4.1 |

mean-R: average for rover
mean-H: average for host
host($Wm^{-2}$) = slope * rover($Wm^{-2}$) + intercept($Wm^{-2}$)
% error = (integrated rover - integrated host)/integrated rover
$\Delta\lambda E$ ($Wm^{-2}$) = average rover $\lambda E$ - average host $\lambda E$
***, **, * significant at 0.1%, 1%, 5% level, respectively, for reject hypothesis slope=1 or intercept=0

*Table 5. Difference in Net Radiation ($Rn_{rover}$ - $Rn_{host}$) as Affected by Radiometer types (Daytime Radiation: $Rn>0$)*

| radiometer type | number of sites | range ($Wm^{-2}$) | mean ($Wm^{-2}$) | standard error | P>T for $H_0$: mean=0 | auto-corr coefficient# |
|---|---|---|---|---|---|---|
| components | 2 | -114.6~53.6 | -8.8 | 4.35 | 0.0493 | 0.355 |
| Didcot | 1 | -71.2~28.2 | -18.1 | 7.79 | 0.0389 | 0.601Y |
| REBS | 10 | -45.6~34.7 | -2.6 | 2.03 | 0.2651 | 0.353N |
| Swissteco | 3 | -53.1~42.5 | 10.2 | 2.49 | 0.0001 | 0.345N |
| Thornthwaite | 1 | -53.9~27.3 | -2.2 | 3.69 | 0.5579 | 0.377Y |

**AOV : Effect of radiometers P > 0.0001**

#: Y indicates significant auto-correlation at 5% level
N means no significant auto-correlation
number along means no decision can be made by D-W statistics.

*Table 6. Difference in Net Radiation ($Rn_{rover}$ - $Rn_{host}$) as Affected by Radiometer types (Nighttime Radiation: $Rn<0$)*

| radiometer type | number of sites | range ($Wm^{-2}$) | mean ($Wm^{-2}$) | standard error | P>T for $H_0$: mean=0 | auto-corr coefficient# |
|---|---|---|---|---|---|---|
| components | 2 | -12.8~17.3 | -1.5 | 1.19 | 0.2301 | 0.240 |
| Didcot | 1 | -32.4-16.3 | -27.4 | 1.31 | 0.0001 | 0.048N |
| REBS | 9 | -8.8~7.0 | 2.9 | 0.51 | 0.0001 | 0.201N |
| Swissteco | 3 | 0.2~30.2 | 13.6 | 0.88 | 0.0001 | 0.349Y |
| Thornthwaite | 1 | -3.8~18.0 | -1.2 | 1.07 | 0.2746 | 0.130Y |

**AOV : Effect of radiometers P > 0.0001**

#: Y indicates significant auto-correlation at 5% level
N means no significant auto-correlation
number along means no decision can be made from D-W statistics

*Table 7. Difference in Bowen Ratio ($\beta_{rover}$ - $\beta_{host}$) as Affected by Instrumentation*

| instrument type | number of sites | range | mean | standard error | P > T for $H_0$: mean=0 | auto-corr. coefficient |
|---|---|---|---|---|---|---|
| **AZET** | 4 | -0.34~0.37 | 0.0010 | 0.0140 | 0.9404 | 0.257 |
| **Camp. Sci.** | 3 | -0.33~0.36 | 0.0133 | 0.0155 | 0.3929 | 0.395N |
| **SERBS** | 6 | -0.16~0.50 | 0.0861 | 0.0086 | 0.0001 | 0.322 |
| **USGS** | 1 | -0.08~0.12 | 0.0181 | 0.0688 | 0.0150 | 0.309 |
| **Eddy Corr.** | 4 | -1.02~1.02 | -0.0201 | 0.0305 | 0.5122 | 0.257N |

**AOV : Effect of instruments P > 0.0001**

#: Y indicates significant auto-correlation at 5% level
N means no significant auto-correlation
number along means no decision can be made from D-W statistics

*Table 8. Difference in Latent Heat Flux ($\lambda E_{rover}$ - $\lambda E_{host}$) as Affected by Instrumentation*

| Rn instrument | β or λE instrument | number of sites | range ($Wm^{-2}$) | mean ($Wm^{-2}$) | standard error | P>T for $H_o$: mean=0 | auto-corr coefficient |
|---|---|---|---|---|---|---|---|
| **components** | **Camp. Sci.** | 2 | -58.9~61.7 | -1.9 | 4.13 | 0.6484 | 0.355 |
| **REBS** | **AZET** | 3 | -36.4~42.8 | 9.5 | 5.32 | 0.1132 | 0.295N |
| **REBS** | **Camp. Sci.** | 1 | -20.2~53.9 | 8.5 | 3.52 | 0.0235 | 0.327N |
| **REBS** | **SERBS** | 6 | -36.1~97.0 | 29.1 | 2.63 | 0.0001 | 0.341 |
| **Swissteco** | **USGS** | 1 | -41.9~51.3 | 15.1 | 5.53 | 0.0134 | 0.289N |
| | **Eddy Corr.** | 3 | -112.1~51.8 | -8.8 | 3.67 | 0.0030 | 0.334 |

AOV: **Effect of adiation P > 0.0001**
**Effect of Bowen Ratio P > 0.0011**

#: Y indicates significant auto-correlation at 5% level
N means no significant auto-correlation
number along means no decision can be made from D-W statistics

Fig. 1. Comparison of host net radiation (Y-axis) and rover net radiation (X-axis) at the FIFE sites.

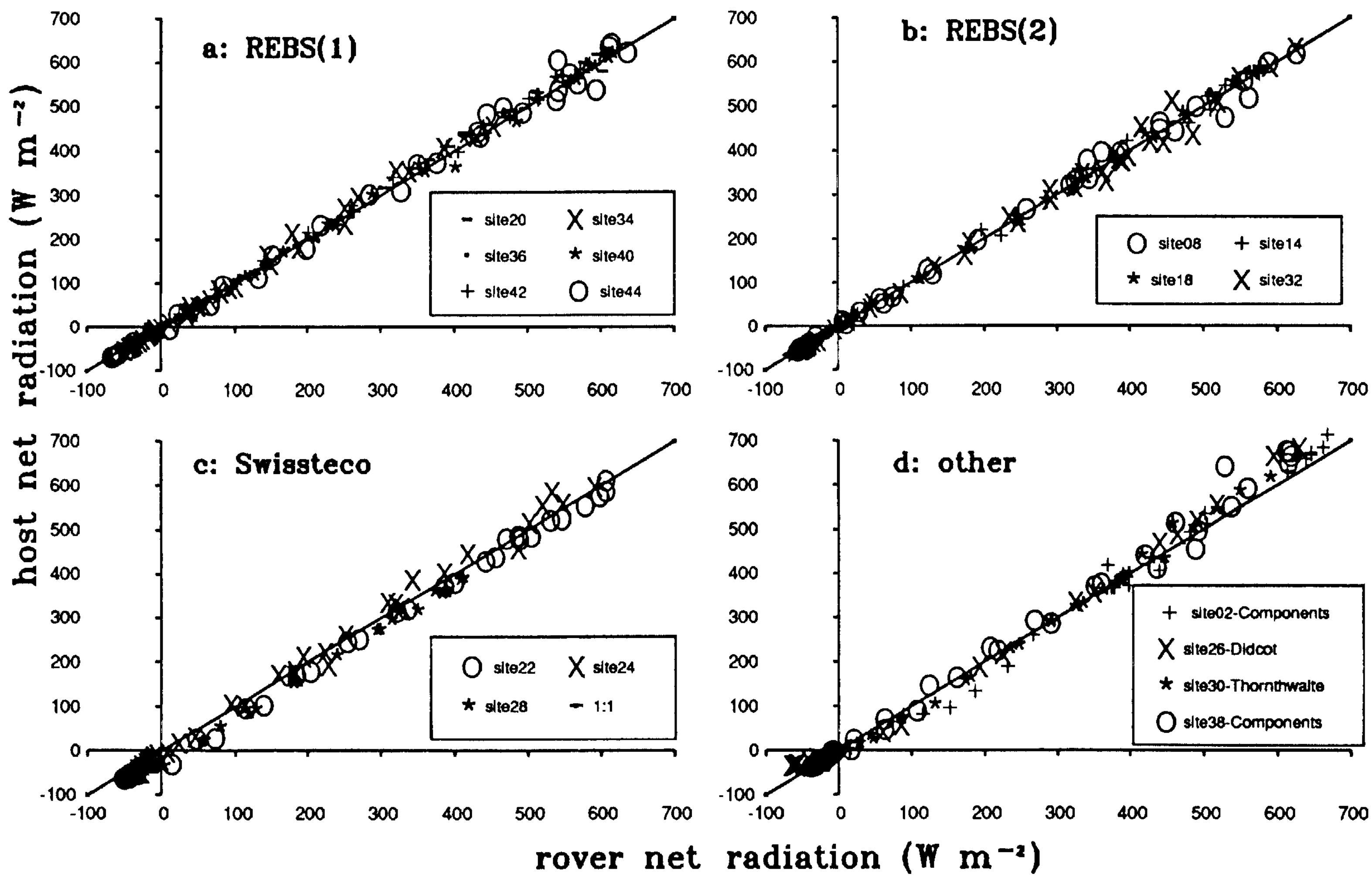

Fig. 2. Comparison of host Bowen ratio (Y-axis) and rover Bowen ratio (X-axis) at the FIFE sites.

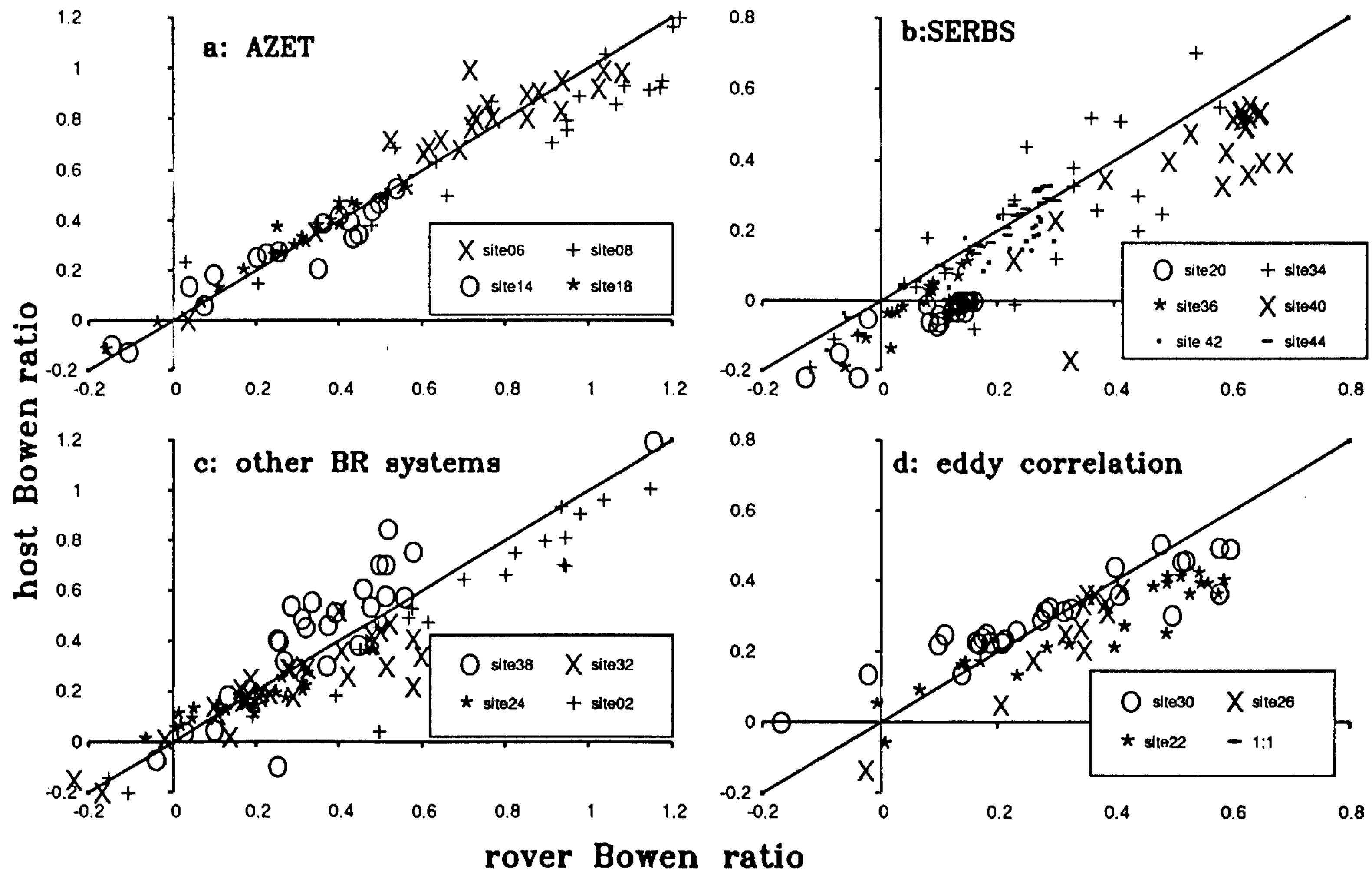

Fig. 3. Comparison of host latent heat flux (Y-axis) and rover latent heat flux (X-axis) at the FIFE sites.